Environment, Development and Sustainability (2024) 26:4487–4503
https://doi.org/10.1007/s10668-022-02892-5

The nutrition-environment nexus assessment of Thai Riceberry product for supporting environmental product declaration

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Received: 3 June 2022 / Accepted: 27 December 2022 / Published online: 12 January 2023

Abstract
Riceberry rice has a special characteristic of being specially bred with high nutrients. High-value added products from riceberry are being promoted targeting health-conscious consumers. To provide supporting information for sustainable food systems, environmental footprinting was applied for evaluating the environmental performance of a ready-to-eat product of riceberry rice mixed with kidney red bean called "Riceberry + KU", developed by Kasetsart University in Thailand. Based on sold unit as the unit of analysis, the carbon footprint of Riceberry + KU was 5.24 gCO_2e per 300 g. Interestingly, white rice had the highest carbon footprint and riceberry rice as well as the riceberry product had at least 30% lower values. However, using nutrient-based scores, although white rice still had the highest carbon footprint, Riceberry + KU had 80% lower and the riceberry rice had 65% lower values. This resulted from the highest nutritional levels found in Riceberry + KU along with the lower greenhouse gas emissions from riceberry field during the cultivation stage. Similar trends were found in the other impact categories assessed by using life cycle assessment as well. To provide appropriate information to consumers for making more sustainable food choices, the environmental performance based on nutrient quality resulting from different farming systems and processing methods should be used to derive recommendations for moving toward sustainable food systems. The nutrition-environment nexus assessment could be very useful for supporting consumers toward making more sustainable food choices.

Keywords Environmental footprint · Life cycle assessment · Sustainable rice production · Thailand

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1 Introduction

Life cycle assessment (LCA) has been applied for assessing the environmental performance of products performing the same functions to identify which product is better in terms of environmental sustainability. The purpose of functional unit is to provide a reference unit to which the inventory data are normalized. The most important issue is functional unit (FU) to be used as a basis for comparison. The definition of FU is often based on the mass of the product under study. However, Mungkung and Gheewala (2007) proposed to consider the nutritional function of food products using a normalization method based on the recommended average daily intake of nutrients. The nutrition-environment nexus, at the product level, could be very useful to provide more appropriate information to consumers for making more sustainable food choices.

It has long been under discussion which functional unit should be used for comparison alternative food products. Different functional units based on mass, edible protein, calories, and land productivity have been used in several previous studies in the food sector (Cederberg & Mattson, 2000; Masset et al., 2015; Saarinen et al., 2017). The results from these studies have shown that different functional units can lead to different conclusions regarding individual foods. For example, the study of Drewnowski et al. (2014) showed that though grains and sweets had low greenhouse gas (GHG) emissions, they had high energy density and low nutrient content. Several studies have proposed to include the nutrient index into the FU; this results in high nutrient animal products such as meat and dairy having relatively lower GHG emission values per kcal as compared to per kg. The study of Smedman et al. (2010), for example, showed that the Nutrient Density to Climate Impact (NDCI) index (nutrient density per GHG) for milk was substantially higher than other beverages. Masset et al. (2015) showed that on a weight basis, food products with animal-based ingredients had much higher impacts as compared to fruit and vegetables as well as starch food, salted snacks and sweets. However, when assessed in terms of nutritional quality, the salted snacks and sweets performed the worst; fruit and vegetables still being environmentally preferable as well as the healthiest choice. Stylianou et al. (2016) considered the nutritional information along with the environmental impacts from LCA study in milk product, expressed as Disability Adjusted Life Years (DALY). Even though adding milk to the diet had an adverse effect on global warming and respiratory inorganics, it had long-term health benefits from reduced risk of colorectal cancer and stroke.

Apart from climate change, water footprint is another impact category that is considered significant for agri-food products. For instance, Ozturk et al. (2022) assessed the change in water footprint caused by the conversion of hazelnut gardens to kiwifruit farms and the results showed that there was a trade-off between water use and economic benefit. Eutrophication is another concern as it closely links with the use of fertilizer for agricultural production systems. For example, Basavalingaiah et al. (2021) used life cycle assessment to compare the environmental impacts of different coffee-pepper farming practices, discovering that the integrated production system had a 7% lower eutrophication impact than the conventional farming system and a 51% lower impact than the organic farming system. Chatzisymeon et al. (2017) also compared the environmental performances of two different open field pepper cultivation systems and found that freshwater eutrophication resulted from greater use of chemical fertilizers with conventional farming scoring thrice as much as organic cultivation. Land use issues gained high interest in connection to land conversion and biodiversity damages. Harun et al. (2021) investigated the cradle-to-gate environmental impacts of conventional and organic farming systems with conventional rice having an impact of 1.84×10^{-6} species year/m^3 and organic rice, 1.30×10^{-6} species year/m^3. Jeswani et al. (2018) investigated the life cycle effects of land use on biodiversity and ecosystem services associated with the production of breakfast cereals and found out that the biodiversity impact was primarily contributed by land use change, accounting for 40–46% of the total impact. Human health issues were also of high interest. Ding et al. (2023) conducted a life cycle assessment (LCA) of the environmental impact of cold and hot break tomato paste production methods and found that the human toxicity-cancer effects of tomato paste using cold and hot break techniques were rather similar, with CTUh values of 3.70×10^{-7} and 3.71×10^{-7}, respectively. Rivera et al. (2017) discovered a similar result, finding that the cancer human health effect of Danish and Italian barley was 46.3×10^{-7} and 51.3×10^{-7} CTUh, respectively, attributed mainly to fertilizer production and agricultural field operations.

In general, the product unit based on a sold unit has commonly been used in the LCA studies of various food products (Beauchemin et al., 2010; Christie et al., 2011; Mungkung et al., 2021). Comparison of the environmental performances among alternative food products has also been reported per protein content (Teixeira et al., 2013; Halloran et al., 2017). Energy use has sometimes been applied for comparing the magnitude of energy use for similar products (Pradhan et al., 2013; Xu et al., 2018). Recently, it has been increasingly discussed that nutritional level in different food products should be a unit of analysis for comparing the environmental impacts associated with the food production systems from the life cycle perspective. For example, as mentioned before, the relative environmental assessment results of meat and plant-based products varied when using a nutrition-based functional unit as compared to a mass-based one (Masset et al., 2015). Another study by Doran-Browne et al. (2015) compared the environmental performance (GHG emissions) of several animal and plant products using mass-based, protein-based, and energy content-based functional units along with that based on nutrient density scores (NDS) using the model developed by Fulgoni et al. (2009). Using the traditional mass-based unit (tCO_2e/t product), wheat flour performed the best, milk and canola oil had similar performance, while meat products performed the worst with lean cuts performing worse that untrimmed cuts. However, using the nutrition-based unit (tCO_2e/NDS) improved the relative performance of meat products reducing the gap with plant products. Within the meat products, lean cuts performed better than untrimmed cuts. Also, milk products (regular and low-fat) performed better than canola oil though wheat flour still had the best performance. In a similar way, the comparative LCAs of food products by using different functional unit showed that beef has the highest GHG emission on a mass-based functional unit (100 g of product); however, beef had fourth rank when using nutrient adequacy scores (Saarinen et al., 2017).

In this study, the life cycle greenhouse gas emissions (carbon footprint) were evaluated for a Thai riceberry rice product based on the sold unit and nutrient-based scores. Riceberry rice, a specially bred rice with high nutrients and antioxidants, has become popular among health-conscious consumers. The novelty of this study is related to a high interest in the beneficial properties of riceberry vis-à-vis health and wellness that have led to research and development in using it as an alternative raw material for high-value added products. In this connection, Thailand has launched a national policy on expanding its cultivation area and processing it into innovative, healthy, and high-value added food products targeting the niche market for health and wellness products that are also friendly to the environment. To respond to the customer requirements and to stimulate the market demand, it was expected that the environmental information of riceberry products based on nutrient levels could be useful to potential consumers for making more sustainable food choices in addition to health and wellness purposes. The environmental performance based on nutrient quality resulting from different farming systems and processing methods was performed to derive recommendations for moving toward sustainable food systems.

2 Materials and methods

2.1 Riceberry rice product development

To support the national policy on high-value added rice products aiming for niche markets, riceberry rice was invented by the Rice Science Center, Kasetsart University (KU), Thailand. Two local rice species—Jao Hom Nin (a local non-glutinous purple rice) and Khao Dawk Mali 105 (Hom Mali rice)—were selected for a crossbreeding process. KU has become a hub for seed production and distribution to the main production sites in the North and Northeast regions due to their suitable climate. In the wet season (May–October) of the year 2018–2019, there were 27 provinces with 1440 hectares growing riceberry rice with an average yield of 84 kg/ha and an average selling price (wet weight) of 0.41 US$ per kg (Department of Agriculture, 2019). In the dry season (January–April), there were 16 provinces with 230 hectares growing riceberry rice with an average yield of 82 kg/ha and an average selling price of 0.45 US$ per kg (Department of Agriculture, 2017). Riceberry rice normally takes at least 130 days to reach maturity. Riceberry offers a high level of both water- and lipid-soluble antioxidants. A dominant antioxidant, anthocyanin, has been linked to reducing cases of diabetes, obesity, and heart disease. Nutritional facts of riceberry rice are given in Table 1. The Thai government has been promoting riceberry rice due to its high nutrition and health properties (National Organic Development Board, 2017). According to the national policy on rice production, the cultivation areas for riceberry rice were to be expanded, aiming to access health-conscious markets in Singapore and EU countries (ThaiTribune, 2015).

Among alternative protein sources, bean is highlighted as a significant source of plant-based proteins. Kidney beans, a variety of the common bean (*Phaseolus vulgaris*), are reddish brown legumes. A 100-g reference amount of cooked red kidney beans (*Phaseolus vulgaris L.*) provides 530 kJ (127 kcal). They are also a rich source of protein (20% or more of the Daily Value, DV), folate (33% DV), iron (22% DV), phosphorus (20% DV), with moderate amounts of thiamin (10–19% DV), and copper, magnesium and zinc (11–14% DV). It has been reported that kidney beans have a very low level in sodium and saturated fatty acids, but a high level in unsaturated fatty acids such as linoleic acid (David et al., 2019). Intake of red kidney beans supports gut health due to the presence of both soluble and insoluble dietary fiber, and also reduces the risk of colon cancer and heart disease (Hayat et al., 2014).

To create an innovative riceberry rice product containing high nutrition with a low environmental impact, food science and technology was integrated with environmental technology and management. Rice is very well known as a main source of carbohydrate in Asia. Although rice has many essential amino acids as its nutritional components, it has low lysine content (Bressani, 2010). Lysine is an essential amino acid that plays an important role in nutrient metabolism and growth of muscle mass for adults and the elderly (Isidori et al., 1981; Fuller et al., 2011). Lack of lysin poses a risk of kwashiorkor in infants

Table 1 Nutritional facts of riceberry rice and red kidney bean (Department of Health, Ministry of Public Health, 2001; Rice Gene Discovery & Rice Science Center (RGD & RSC), Kasetsart University, 2015)

Nutrients	Quantity (Sold unit, 100 g per package)	
	Riceberry rice	Red kidney bean
Energy (kCal)	390	346
Carbohydrates (g)	80.00	63.30
Fat (g)	4.00	2.20 g
Protein (g)	8.00	18.20 g
Fiber(g)	6.6	23.8
Vitamins		
Vitamins A (μg)	63.00	0.00
Folate (μg)	48.00	0.00
Vitamins E (mg)	0.68	–
Vitamin B1 (mg)	–	0.16
Vitamin B2 (mg)	–	1.32
Vitamin B3 (mg)	–	2.70
Vitamin C (mg)	–	2.12
Minerals		
Iron (mg)	1.3–1.8	8.2
Omega-3 (mg)	25.51	301
Sodium (mg)	50.00	0.00
Zinc (mg)	3.20	3.49
Calcium (mg)	–	115
Magnesium (mg)	–	140
Potassium (mg)	–	1371
Antioxidants		
Gamma-oryzanol (μg)	0.46	–
Tannin (mg)	89.33	2.98
Anthocyanin (mg)	15.7	–
Leutein (mg)	45	–
Water-soluble antioxidant (mg ascorbic acid equivalent)	47.5	–
Oil-soluble antioxidant (mg trolox equivalent)	33.4	–

(Albanese et al., 1956). A lysine deficient diet can reduce immunity, decrease protein levels in the blood, and cause retardation of mental and physical development in children (Galili & Amir, 2013).

By completing the essential amino acids profile, the addition of plant-based protein by using red kidney bean (*Phaseolus vulgaris* L.) has been reported to have a high lysine content which is not affected by cooking (Audu & Aremu, 2011). In this connection, the Institute of Food Research and Product Development, Kasetsart University, Thailand, has created and developed ready-to-eat riceberry mixed with red kidney bean called "Riceberry + KU" (Fig. 1). The product development was based on the optimization of amino acid profiles of riceberry rice mixed with red kidney beans as a complementary nutrient requirement of lysine. Based on the nutritional composition analysis, Riceberry + KU had higher protein while offering a similar level of energy, fat and carbohydrate as cooked

Fig. 1 Riceberry + KU product, which is riceberry rice mixed with red kidney bean

riceberry rice (Satmalee et al., 2019). The main ingredients are riceberry rice 90% and red kidney bean 10%. Sodium and phosphate salts are added in order to improve texture properties (harder and firmer product) (Satmalee et al., 2019).

As mentioned earlier, riceberry rice is enriched with a high level of nutrients but lacks lysine. Beans are one of the few plant foods rich in lysine and the amount of lysine is not reduced after cooking (Audu & Aremu, 2011; Supreetha et al., 2009). In fact, the lysine content in brown rice kernels was increased from 0.7 mg/100 g to 2.12 g/100 g when cooked (Rodríguez-Bürger et al., 1998; Saikusa et al., 1994). To improve the riceberry amino acid profiles, plant-based protein from red beans was then added as a supplementary source to have a wide-ranging essential amino acid profile of Riceberry + KU product by mixing riceberry with red bean. Essential amino acid content of Riceberry + KU product is presented in Satmalee et al. (2019). The required inventory data were identified along the life cycle production activities. Riceberry rice (unpolished) was obtained from the Rice Science Center at Kasetsart University, while red beans were sourced from a local market. Data on cooking of red bean mixed with riceberry rice were obtained from a previous study (Satmalee et al., 2019). The life cycle inventory data based on the unit of analysis (100 g) of Riceberry + KU product are shown in Table 2 (Fig. 2).

2.2 Environmental footprint based on the nutritional functional unit

The environmental footprint of Riceberry + KU product based on the nutrient-based scores and sold unit as functional unit was evaluated to compare its performance with the normal riceberry rice product. Along all the life cycle stages of riceberry product, the associated inputs and outputs were identified, and data were gathered based on the production cycle in 2018. The inventory data were collected based on the average values from 3 batch-based production cycles at a laboratory-based experiment. The background data were sourced primarily from the national databases (Thailand Greenhouse Gas Management Organization (Public Organization), 2020) and supplemented by the international databases (i.e., ecoinvent version 3.6) embedded in an LCA software (SimaPro Version 9.1.0.7). Environmental impacts included in the calculation of environmental footprints were climate change, cancer human health effects, eutrophication freshwater, land use, and water scarcity based on the Product Environment Footprint method (PEF) following the key issues associated with

Table 2 List of the life cycle inventory data of 100 g Riceberry + KU product

Life cycle stage/List of inventory data	Quantity	Inventory data (unit)
Raw materials acquisition		
Riceberry rice	43.50	g
Red bean	3.44	g
Sodium salt	1.71×10^{-1}	g
Phosphate salt	7.41×10^{-2}	g
Retort pouch	6.78	g
Ink for date labelling	4.87×10^{-2}	g
Corrugated box	7.70	g
Ink for packaging	6.55×10^{-3}	ml
Production processing		
1. Preparing ingredients		
Inputs		
Riceberry rice	43.5	g
Red bean	3.44	g
Electricity	1.93×10^{-2}	kWh
Water	68.60	ml
Outputs		
Boiled riceberry rice	43.50	g
Boiled red bean	3.44	g
Wastewater	68.60	ml
2. Steaming		
Inputs		
Boiled riceberry rice	40.35	g
Boiled red bean	3.44	g
Water	12.90	ml
LPG	8.08×10^{-2}	g
Outputs		
Boiled riceberry rice	61.60	g
Boiled red bean	6.60	g
Wastewater	12.90	ml
3. Mixing		
Inputs		
Riceberry rice	61.60	g
Red bean	6.60	g
Sodium salt	1.71×10^{-1}	g
Phosphate salt	7.41×10^{-2}	g
Water	17.10	ml
Outputs		
Riceberry mixed with red bean	85.5	g
4. Packing		
Inputs		
Riceberry mixed with red bean	85.5	g
Retort pouch	6.78	g
Electricity	6.97×10^{-4}	kWh

Table 2 (continued)

Life cycle stage/List of inventory data	Quantity	Inventory data (unit)
Outputs		
Riceberry mixed with red bean in retort pouch	92.30	g
5. Sterilizing		
Inputs		
Riceberry mixed with red bean in retort pouch	92.30	g
Electricity	4.40×10^{-2}	kWh
Diesel	10.30	ml
Water	240.00	ml
Outputs		
Sterilized product	92.30	g
6. Date labelling		
Inputs		
Sterilized product	92.30	g
Corrugated box	7.70	g
Ink for date labelling	4.87×10^{-2}	ml
Ink for corrugated box	6.55×10^{-3}	ml
Electricity for motor	2.53×10^{-5}	kWh
Electricity for date labelling machine	1.01×10^{-4}	kWh
Output		
Riceberry mixed with red bean in retort pouch	100.00	g
Support processing		
Input		
Electricity for lighting systems	1.71×10^{-6}	kWh
Electricity for ventilation systems	6.69×10^{-6}	kWh
Distribution		
–	–	–
Consumption		
Electricity	1.00×10^{-2}	kWh
Waste disposal		
Retort pouch	6.78×10^{-3}	g
Corrugated box	7.70×10^{-3}	g

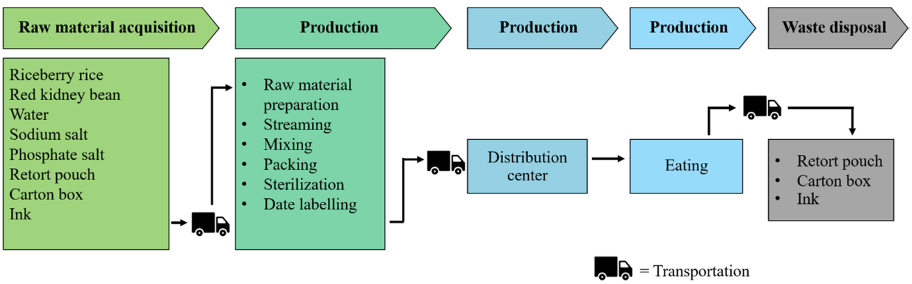

Fig. 2 The life cycle flowchart of Riceberry + KU product

food products identified earlier (Habibi et al., 2019; Nizamani et al., 2019). The global warming potential factors for calculating carbon footprint were from the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2013).

The nutrient-based scores were referred from the Nutrient-rich indices (NRn) or nutrient balance score (NBS) originally developed by Fulgoni et al. (2009). It was used for measuring the nutritional quality of foods from a nutrient density index score. The nutrients to encourage ($n=6$, 9) and nutrients to limit (LIM) were based on a fixed number ($n=3$). In this study, the nutrient-rich scores (NR6.3 and NR9.3) were applied, the details of which are given in Table 3.

The NRn was calculated by Eq. (1)

$$\text{NR n.3} = \sum_{i=n} \frac{\text{nutrient}_i}{\text{DRI}_i} \times 100/n - \sum_{i=1-3} \frac{\text{nutrient}_i}{\text{DA}_i} \times 100/3 \tag{1}$$

in which nutrient means amount of nutrient$_i$ in 100 g of a food product. DRI$_i$, daily recommendation for intake of nutrient$i$, is a set of reference values used to plan and assess nutrient intakes of health-conscious people. DA$_i$, daily allowance for intake of nutrient$_i$, is a reference set of the nutrients to be limited. This paper referred the DRI and DA values from dietary reference intake for Thai people (Bureau of Nutrition, Department of Health, Ministry of Public Health, 2020).

This study used the nutrition carbon footprint score (NCFS) to calculate nutrition per global warming impact following Eq. (2). This was used as an indicator of the product nutrient density per environmental impact following Chaudhary et al. (2018).

$$\text{NCFS} = \frac{\text{NR}_n}{\text{Global warming}} \tag{2}$$

3 Results and discussion

3.1 Nutrient-based scores assessment

The nutrition information of Riceberry + KU was analyzed by the Food Quality Assurance Service Center (FQA), Kasetsart University and Satmalee et al. (2019). The nutritional quality of riceberry rice and white rice was additionally gathered from the nutritive values of Thai foods and published data from the Department of Rice (Department of Health, Ministry of Public Health, 2001; Rice Gene Discovery & Rice Science Center (RGD & RSC), 2015). Apart from the national databases, FoodData Central of U.S. Department of Agriculture was also referred to for some missing nutrient data (U.S. Department of Agriculture, 2021). The calculation of nutrient-based scores was performed by using Eq. (1).

Table 3 The nutrients to encourage and the nutrients to limit for nutrient-based score (NRn) calculation

Nutrient-based score	The nutrients to encourage	The nutrients to limit
NR6.3	Protein, fiber, vitamin A, vitamin C, calcium, iron	Saturated fat, added sugar, sodium
NR9.3	Protein, fiber, vitamin A, vitamin C, calcium, iron plus vitamin E, magnesium, potassium	Saturated fat, added sugar, sodium

Table 4 Nutrient-based scores of different rice products

Nutrients	Thai DRI/DA	Nutrition			Nutrients/DRI		
		Riceberry + KU	Riceberry rice	White rice	Riceberry + KU	Riceberry rice	White rice
Energy (kCal/day)	2000	217	365	356	0.11	0.18	0.18
Fiber (g)	25	6.24	3.68	0.60	0.25	0.15	0.02
Protein (g)	50	5.79	8.02	6.20	0.12	0.16	0.12
Ca (mg)	800	29.03	10.00	3.00	0.04	0.01	0.00
Fe (mg)	15	1.21	1.45	–	0.08	0.10	0
Vit A (μg RE)	800	40.00	–	–	0.05	–	0
Vit C (mg)	60	–	–	–	–	–	0
Vit E (mgα-TE)	10	0.34	0.68	0.04	0.01	0.01	0.00
Mg (mg)	350	1.11	–	12.00	0.02	–	0.20
K (mg)	3500	117.82	123.00	35.00	1.96	2.05	0.58
Na (mg)	24,000	109.69	0.77	245	0.00	0.00	0.01
Saturated fat (g)	20	0.68	0.93	0.077	0.03	0.05	0.00
Added sugar (g)	65	0.38	1.82	0.05	0.01	0.03	0.00
NR6.3 score					7.39	4.46	2.03
NR9.3 score					26.52	25.05	9.90

DRI, daily recommendation for intake of nutrient; DA, was a daily allowance for intake of nutrient

The nutrient-based scores, either NR6.3 or NR 9.3, are shown in Table 4. In general, Riceberry + KU had the highest score, followed by riceberry rice and white rice, respectively, as the Riceberry + KU had higher fiber and Ca content with lower SAFA content. It was found that the conventional riceberry has higher nutritional levels for most the nutrients compared to white rice. By adding the red bean into conventional riceberry, it turned out that Riceberry + KU contains significantly higher fiber, Ca, Mg, Vit A, and Na while lowering the quantities of energy and saturated fat. The result was also similar to Chaudhary et al. (2018) where the replacement of wheat flour by whole yellow pea flour could lead to higher nutrient-rich score with lower global warming impact. Furthermore, the amount of energy in 100 g of Riceberry + KU product was also lower (217 kcal/day) than riceberry rice (365 kcal/day) and white rice (356 kcal/day) (Satmalee et al., 2019; Department of Health, Ministry of Public Health, 2001; Rice Gene Discovery & Rice Science Center (RGD & RSC), 2015).

3.2 Life cycle impact assessment

The LCA results are presented in Table 5, by firstly explaining the carbon footprint or global warming. This was mainly because the concept design of product development of Riceberry + KU was based on the strategies to reduce carbon footprint. After that, the other impact categories are presented and discussed to identify if there was any trade-off or problem-shifting between impacts. Table 5 shows the results of carbon footprinting based on the sold unit (300 g) and nutrient-based functional unit (in this study, 100 g of similar nutrient was used). The impact assessment results of global warming using the sold unit revealed that the white rice product had the highest impact followed by riceberry rice and Riceberry KU +, respectively (Table 5). The global warming of white rice was almost 30% higher than both riceberry rice and Riceberry KU +, that was simply because the direct GHG emissions from rice field of white rice (5.58 ± 0.44 kg CH_4/ha/day) were higher than that from riceberry rice field from previous study (4.12 ± 3.26 kg CH_4/ha/day) (Jermsawatdipong et al., 1994; Katoh et al., 1999). It was found that Riceberry + KU and the normal riceberry rice product had similar impacts, as the red bean production and processing required only a little more energy and water. The white rice had the highest carbon footprint value even when using the nutrient-based functional unit. However, it turned out that Riceberry + KU had the lowest carbon footprint value when considering the nutrients by using NR6.3 method; moreover, the carbon footprint values of Riceberry + KU was 80% lower than white rice while that of riceberry rice was almost 65% lower than white rice. Interestingly, the Riceberry + KU had the lower carbon footprint values compared to the

Table 5 Comparative carbon footprint of Riceberry + KU based on the sold units and nutrient-based scores

Rice products	Carbon footprint based on sold unit ($kgCO_2e$/300 g)	Carbon footprint based on nutrient-based functional unit (100 g)			
		Nutrient-based score		Carbon footprint score per	
		NR6.3	NR9.3	NR6.3 ($kgCO_2e$/100 g)	NR9.3 ($kgCO_2e$/100 g)
Riceberry + KU	5.24E−03	7.39E+00	2.65E+01	2.02E−04	5.63E−05
Riceberry rice	5.22E−03	4.46E+00	2.50E+01	3.34E−04	5.94E−05
White rice	7.16E−03	2.03E+00	9.90E+00	1.00E−03	2.06E−04

normal riceberry rice which resulted from the highest nutritional levels in Riceberry + KU, followed by riceberry rice and white rice, respectively. The results corresponded with the previous studies where using different functional units led to different results and different implications (Saarinen et al., 2017; Drewnowski et al., 2014; Masset et al., 2015) (Fig. 3).

The LCA results in Fig. 4 show that the raw material acquisition stage is the major contributor to the impacts of land use (98%) and water scarcity (94%), whereas the processing stage is primarily responsible for eutrophication freshwater (79%), cancer human health effects (62%), and climate change (61%), which are primarily caused using electricity for packing, sterilizing, and date labeling processes. In addition, Table 5 shows the comparative environmental footprints of Riceberry + KU, riceberry, and white rice based on the sold unit and nutrient-based scores. All the impact categories considered showed the same trend and relative performance among the various options being compared was also similar confirming that there is no trade-off between carbon footprint with other impacts (Fig. 5).

4 Conclusions

Riceberry rice has emerged as an alternative rice enriched with anthocyanin and antioxidants with significant levels of beta-carotene, gamma oryzanol, vitamin E, folic acid, tannin, zinc, fiber, and bran oil. The nutrient-rich properties of riceberry rice have been linked to reducing cases of diabetes, obesity, and heart disease. As a consequence, it has been gaining a high interest among health-conscious consumers for both domestic and international markets. At the same time, the environmental performance based on LCA has been questioned due to the current challenge on food security in terms of sustainable food systems along with comparison of alternative food products for consumers to make more sustainable food choices. However, the unit of analysis in LCA was so far mostly based on the sold unit of food products. This did not reflect the real reason behind the function of food products to provide the nutrition and therefore the better choice for promoting sustainable consumption and production. This study demonstrated the application of LCA based on sold unit compared to nutrient-based functional unit. The results showed that the

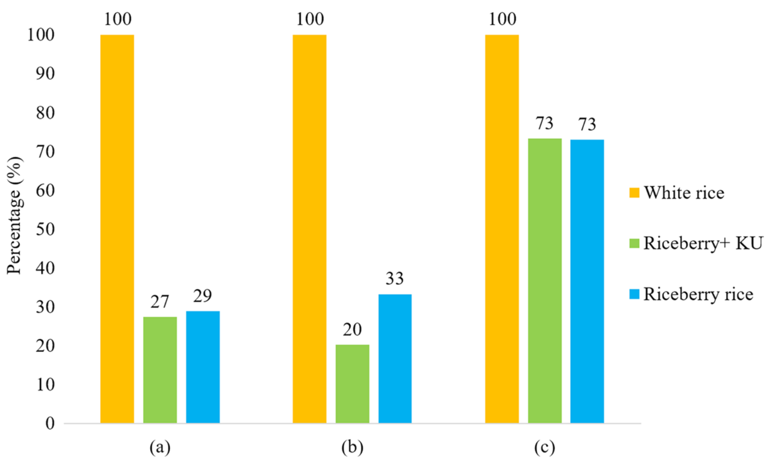

Fig. 3 Comparative carbon footprint values of different rice products using the **a** NR9.3, **b** NR6.3, **c** sold unit

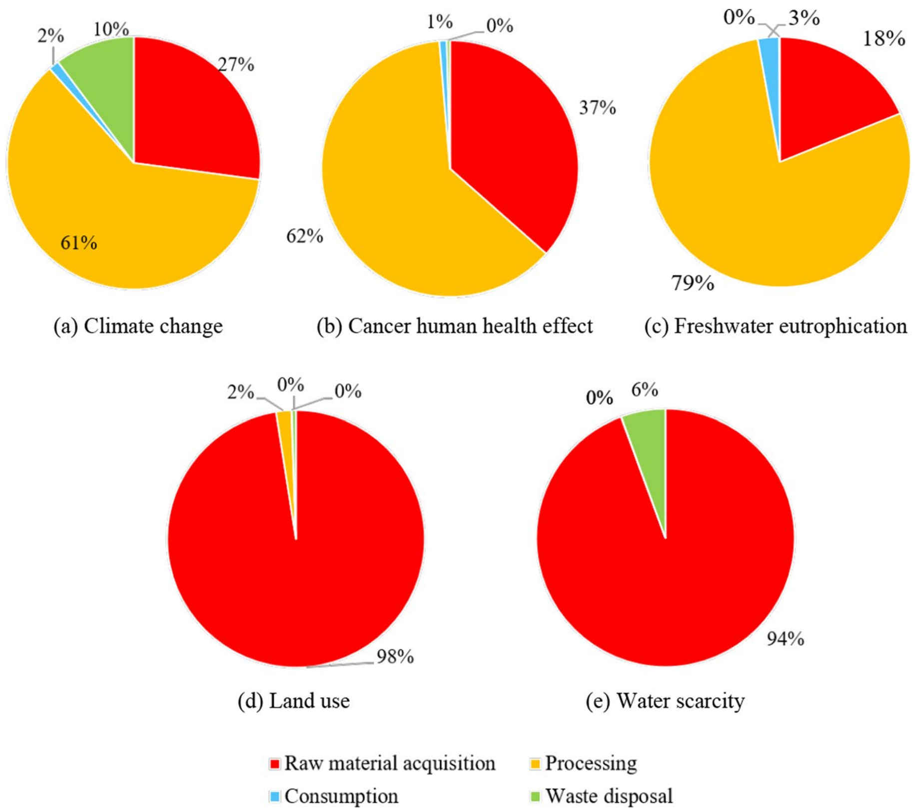

Fig. 4 The percentage contribution of process stages to the evaluated impacts categories **a** climate change, **b** cancer human health effect, **c** freshwater eutrophication, **d** land use and **e** water scarcity

decisions could be totally different when comparing similar food products performing the same functions based on sold unit and nutrient-based functional unit. It was revealed that the white rice had an at least 30% higher carbon footprint when compared to the normal riceberry rice and Riceberry KU+. Using a different functional unit could lead to different results leading to different implications. By considering protein, fiber, vitamin A, vitamin C, calcium, iron included in the nutrient index in terms of nutrition-based score NR6.3, the carbon footprint value of Riceberry+KU turned out to be significantly lower than the normal white rice (80%) and riceberry rice (15%). When taking into account of vitamin E, magnesium, potassium in addition as described in the nutrition-based score NR9.3, the results were similar to NR6.3; this was because Riceberry KU+had a higher amount of magnesium and potassium than other rice products. This resulted from the highest nutritional levels were found in in Riceberry+KU along with the lower GHG emissions from riceberry rice field during the cultivation stage. The LCA results on other potential environmental impacts also confirm that there is no trade-off between carbon footprint and other impact categories. Performing LCA of food with the consideration of nutritional values could enhance our understanding leading to a more reasonable interpretation of the environmental performance based on nutritional functions. The nutrition-environment nexus, at the product level, could be very useful to provide more appropriate information

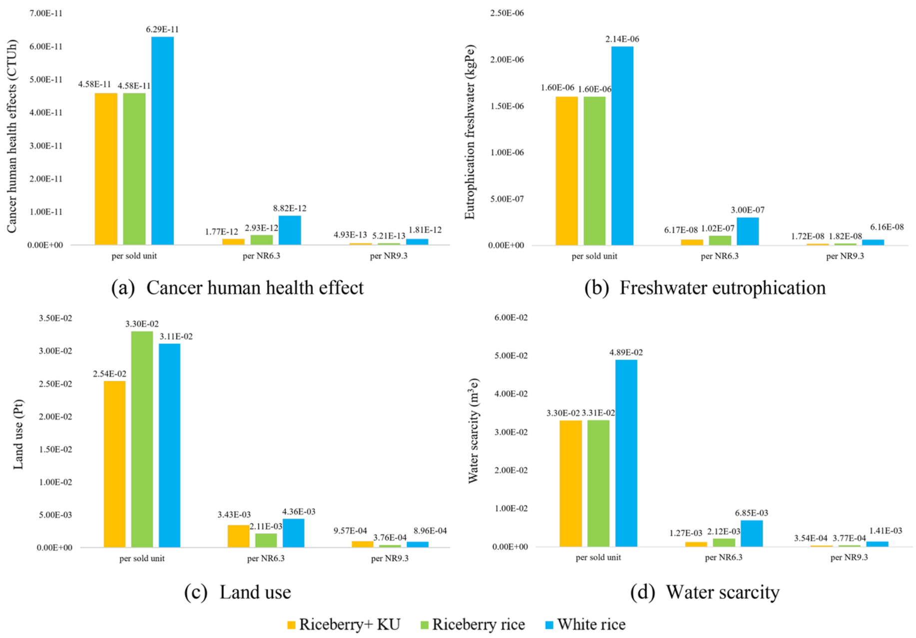

Fig. 5 Comparative environmental footprints of Riceberry + KU based on the sold unit and nutrient-based scores **a** cancer human health effect, **b** freshwater eutrophication, **c** land use and **d** water scarcity

to consumers for making more sustainable food choices. By incorporating the nutritional aspects, recommendations can be developed on how to produce more responsibly and moving toward sustainable consumption and production.

Acknowledgements Acknowledgement is given to the (National Science and Technology Development Agency) Research Chair Grant program under the project "Network for Research and Innovation for Trade and Production of Sustainable Food and Bioenergy" (Grant No. FDA-CO-2559-3268-TH) for the financial support.

Data availability The data presented in this study are available on request from the corresponding author.

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